

# Fast Imaging Detector Readout Circuits with In-Pixel ADCs for Fourier Transform Imaging Spectrometers

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**Abstract:** Focal plane arrays (FPAs) with high frame rates and many pixels benefit several upcoming Earth science missions including GEO-CAPE, GACM, and ACE by enabling broader spatial coverage and higher spectral resolution. FPAs for the PanFTS, a high spatial resolution Fourier transform spectrometer and a candidate instrument for the GEO-CAPE mission are the focus of the developments reported here, but this FPA technology has the potential to enable a variety of future measurements and instruments.

The ESTO ACT Program funded the development of a fast readout integrated circuit (ROIC) based on an innovative in-pixel analog-to-digital converter (ADC). The 128 X 128 pixel ROIC features 60  $\mu\text{m}$  pixels, a 14-bit ADC in each pixel and operates at a continuous frame rate of 14 kHz consuming only 1.1 W of power. The ROIC outputs digitized data completely eliminating the bulky, power consuming signal chains needed by conventional FPAs.

The 128 X 128 pixel ROIC has been fabricated in CMOS and tested at the Jet Propulsion Laboratory. The current version is designed to be hybridized with PIN photodiode arrays via indium bump bonding for light detection in the visible and ultraviolet spectral regions. However, the ROIC design incorporates a small photodiode in each cell to permit detailed characterization of the ROIC performance without the need for hybridization. We will describe the essential features of the ROIC design and present results of ROIC performance measurements.

## I. FAST IMAGING FOCAL PLANE ARRAY APPLICATIONS

Fast Imaging Focal Plane Arrays (FPAs) which provide high throughput have many NASA Earth science space mission applications. Missions recommended in the National Research Council Earth Science Decadal Survey [1] such as the Geostationary Coastal and Air Pollution Events (GEO-CAPE) mission, and the Global Atmospheric Composition Mission (GACM) would greatly benefit from high throughput digital FPA technology. These missions will make frequent measurements of the spatial and temporal variabilities of trace gases and aerosols that influence air quality and climate change. Photochemical transformations and regional-scale transport of pollutants occurs on time scales from minutes to hours, especially in the planetary boundary layer. The time scales of variability of these processes require frequent, high-spatial-resolution and high-

temporal-resolution measurements. Such measurements will enable the determination of natural and anthropogenic emissions of pollutants and trace gases that result in the formation of tropospheric ozone and aerosols. Data products such as these will be extremely valuable to the research community as well as to operational agencies such as NOAA and EPA which are responsible for developing effective air pollution mitigation strategies.

A primary objective of the GEO-CAPE mission is to measure the atmospheric composition over North and South America about once per hour. High resolution measurements many times a day are required to capture the rapidly changing chemistry in the troposphere, especially near the Earth's surface. Frequent observations also enable quick detection and monitoring of highly dynamic atmospheric events caused by volcanoes, fires, hurricanes, and severe weather. High throughput digital FPAs provide the ability to make measurements quickly, hence more frequently, thus allowing systematic observations of atmospheric chemistry and detection of pollution events.

As described in the Decadal Survey, atmospheric composition measurements will be made with a UV-visible-near-IR imaging spectrometer. An imaging spectrometer instrument concept that could fully accomplish these measurements is the Panchromatic Fourier Transform Spectrometer (PanFTS) which was selected for development by the NASA Earth Science Technology Program 2007 and 2010 Instrument Incubator Program [2,3]. The PanFTS flight instrument concept is a medium size instrument designed to use high throughput digital FPAs for accomplishing the science objectives of the GEO-CAPE mission. PanFTS and other imaging spectrometers need fast 2D focal plane arrays to rapidly record spectra in every pixel. Our FPAs will dramatically improve spectral, spatial and temporal resolution measurements for missions like GEO-CAPE.

Our innovative high throughput digital focal plane array design provides a digital output for each pixel which eliminates the need for off-chip signal chain electronics. This technology will benefit a number of future earth science missions by substantially reducing FPA signal chain complexity, volume, mass and power. The functionality of an all-digital FPA will greatly simplify instrument design by eliminating the bulky, power consuming signal chains needed by conventional FPAs which will reduce implementation risk and cost.

## II. HIGH THROUGHPUT DIGITAL FPA DESIGN

Hybrid FPAs typically consist of a photo-sensitive diode pixel array electrically connected to a readout integrated circuit (ROIC) as illustrated in Fig.1. The photo-sensitive array is bump-bonded (hybridized) to the ROIC with indium metal bumps. This approach provides great flexibility in that the detector array and readout electronics can be individually optimized for different applications.

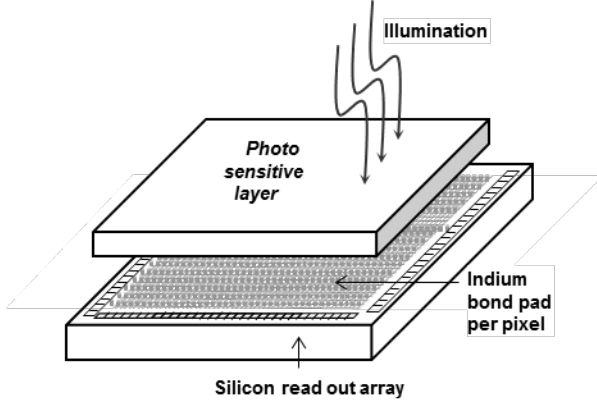


Fig. 1 Hybrid FPA architecture

The ROIC is the heart of a digital FPA. In our 128X128 pixel array ROIC each pixel has its own 14-bit analog-to-digital converter. This in-pixel ADC approach provides fast frame rates without requiring extraordinary speed in the ADC as would be the case if each ADC had to handle the multiplexed output from several pixels. Additionally, analog-to-digital conversions are done in all pixels simultaneously, enabling snap shot operation rather than a “rolling shutter” readout. All pixels are read out at the same time which eliminates problems with conventional rolling shutter readouts where pixels are read out sequentially introducing artifacts from crosstalk between pixels when adjacent pixels reset. Fig. 2. shows the unit cell ADC layout. This unit cell circuitry is included in each of the 16, 384 pixels. A small photodiode was included in the unit cell layout to enable some preliminary testing of the ROIC as an FPA. While the photodiode it is too insensitive for the intended science measurements, it has been invaluable for demonstrating the essential features of the ROIC.

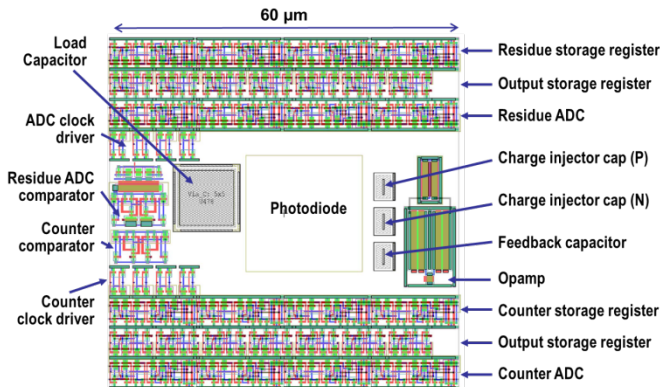


Fig. 2. Single pixel ADC layout

Fig. 3. shows the layout of the chip that was manufactured.

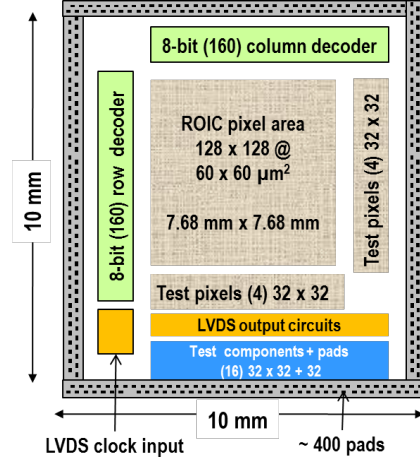


Fig. 3. ROIC chip floor plan

The digital control and interface circuitry is laid out around the periphery of the 128X128 array. The design also includes several test circuits. The test circuits are sub elements of the ADCs and standalone pixels. This allowed the functional elements of a pixel to be tested independently and their performance assessed relative to the performance expected for their design. This was also done for complete standalone pixels. The test circuits measurements showed that the input amplified accurately integrates the photodiode current, and the charge injector subtraction, a key element of the ADC approach, works with the accuracy needed to make high precision ADCs. Other elements of the design verified with test circuits included that the counter comparator reliably triggered the charge subtraction, that the sample and hold at the output of the input stage maintained the output voltage for residue sampling and that all bits down to the LSB was responds to appropriate levels at the input. It also showed that the ADC design and layout operated with 14 bit precision.

## III. HIGH THROUGHPUT DIGITAL FPA TESTS

Fig. 4. Shows the ROIC chip in the laboratory test set up.

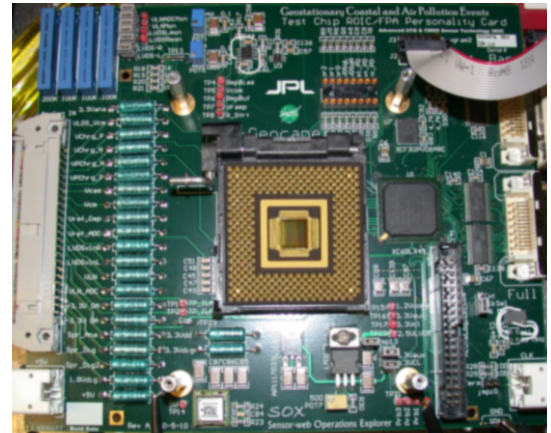


Fig. 4. ROIC chip in the laboratory test set up

Laboratory testing has verified many of the key performance characteristics of the array and the 229 million pixels per second output at 14 bits. Some of these are summarized in Table I.

Table 1. In-Pixel ADC ROIC measured characteristics

Characteristic	Measured Value
ADC Resolution	14 bits
Read Out Frame Rate	14 kHz
Nonlinearity (ADC readout proportionality to photon flux)	< 0.1%
Total Noise	< 100 e- per sample
Spectral Range of Photodiode	~400 - 900 nm
Total Power Consumption	1.1 W @ 14 kHz

However, testing of the ROIC as the detector in an imaging interferometer has provided the most important and relevant performance testing of the device to date. We are fortunate the Fourier Transform Ultraviolet-Visible Spectrometer (FTUVS) at JPL's Table Mountain Facility [4] shown in Figure 5 was available to support ROIC testing. Stanley Sander is the PI for the FTUVS which is a sun viewing Michelson interferometer used to routinely acquire high-resolution solar spectra to measure total column abundances of OH, NO<sub>3</sub>, CO<sub>2</sub>, BrO, and other species [5].

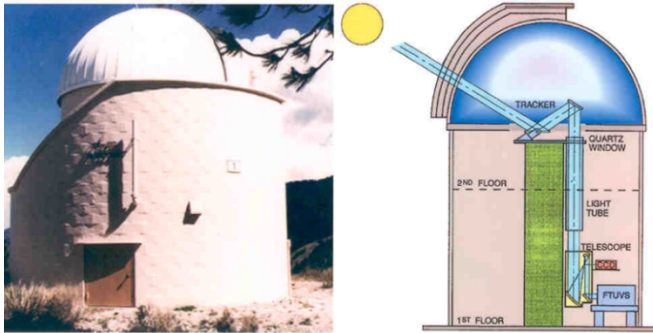


Fig. 5. Fourier Transform UV Spectrometer (FTUVS) at the JPL Table Mountain Facility (TMF)

This unique testing arrangement demonstrated the ROIC performance in a relevant environment (TRL 5). The ROIC was substituted for the existing detector at the exit focus of the FTUVS as shown in Fig. 6. This set up allowed the ROIC to capture interferograms as it would in a spaceborne spectrometer

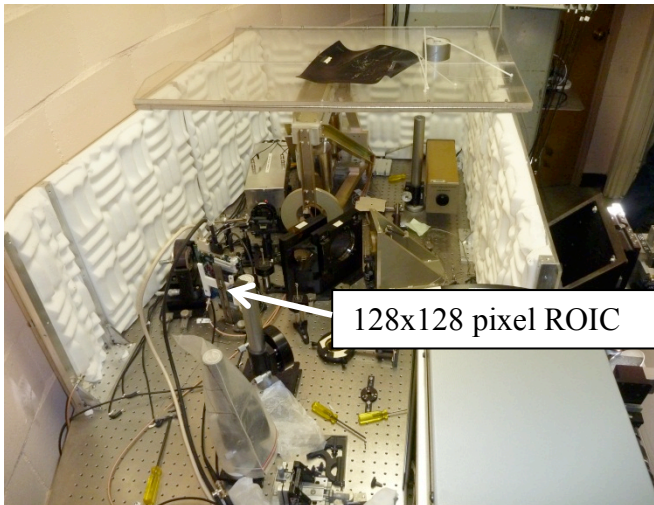


Fig. 6. In-Pixel ADC ROIC in the FTUVS instrument

The optical train was configured so that the solar image illuminated the ROIC array as shown in Fig. 7. Interferograms were recorded for maximum optical path difference of 1 cm. The spectrum of each pixel was calculated with the JPL-developed software routinely used for FTUVS.

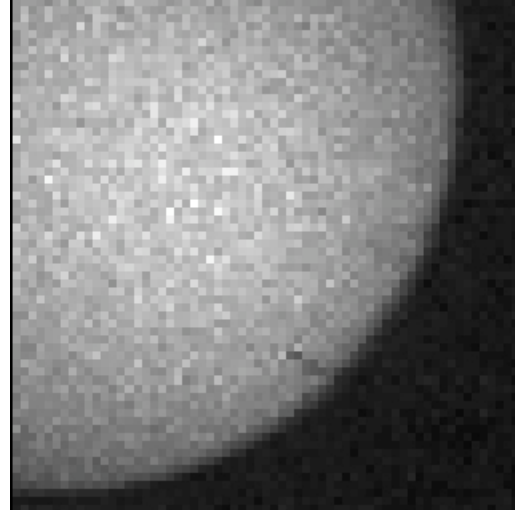


Fig. 7. The solar disk imaged by the ROIC through FTUVS

Fig. 8 shows a typical interferogram recorded by the ROIC.

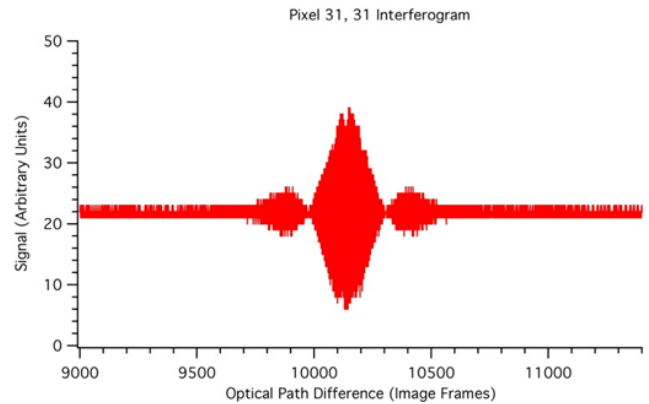


Fig. 8. Typical Interferogram recorded with FTUVS by the ROIC

Fig. 9 shows the spectrum acquired by a typical ROIC pixel when imaging the sun through the FTUVS with an optical filter limited to the spectral region near 760 nm.

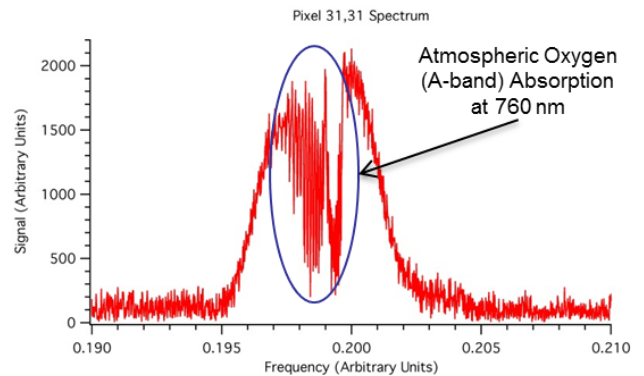


Fig. 9. O<sub>2</sub> A-band spectrum acquired by a ROIC pixel

The spectrum acquired by the ROIC in FTUVS clearly shows atmospheric oxygen (A-band) absorption at 760 nm. This result demonstrates that the ROIC is capable of supporting the high throughput atmospheric composition measurements like those called for in the Decadal Survey.

The built-in photodiode enabled the demonstration of ROIC performance, but does not have the sensitivity to yield results representative of the capabilities possible when the ROIC is hybridized with a high performance science detector array of silicon PIN diodes.

#### IV. FUTURE HIGH THROUGHPUT DIGITAL FPA DEVELOPMENT

The current ROIC was manufactured with a built-in silicon photodiode in each pixel to enable testing the ROIC without the need to hybridize it. However, the photodiode reduced the space available for the ADC circuitry which consequently had to be limited to 14 bit resolution to fit in the 60 micron pixel. Future developments will focus on hybridizing the existing ROIC with a silicon PIN diode photosensitive detector array. The resulting digital FPA will be tested to verify the overall performance of the hybridized array and identify refinements for improving FPA performance. From there the next advance will be to modify the ADC design to provide 16 bit resolution. The additional circuitry needed for this will not leave space for a built in photodiode. Therefore, the optimized ROIC will be hybridized to a silicon PIN diode photosensitive detector array for testing. GEO-CAPE atmospheric composition measurements required NIR to UV spectral sensitivity so a photosensitive material such as silicon PIN with good response across that wavelength range will contribute to optimal FPA performance.

#### ACKNOWLEDGMENTS

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